Machine learning for ultrafast nonlinear photonics

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*Abstract*—We review our recent progress on the application of machine-learning techniques in the field of ultrafast nonlinear fibre optics. We demonstrate that neural networks can both efficiently predict the temporal and spectral features of optical signals that are obtained after propagation in the presence of focusing and defocusing nonlinearity and solve the associated inverse problem. We also show that evolutionary algorithms can be used to control complex nonlinear dynamics of ultrafast fibre lasers.

Keywords—nonlinear photonics, fiber optics, machine learning

Recent years have seen the rapid growth of the field of smart photonics where the deployment of machine-learning strategies is the key to enhance the performance and expand the functionality of optical systems. Ultrafast photonics areas where the promise of machine learning is being realised include the design and operation of pulsed lasers, and the characterisation and control of ultrafast propagation dynamics [1]. Here, we review our recent results in the field by providing several examples of advances enabled by machine-learning tools such as neural networks (NNs) and evolutionary algorithms (EAs).

First, we describe the use of a supervised feedforward NN paradigm to solve the direct and inverse problems relating to nonlinear pulse shaping in optical fibres, bypassing the need for direct numerical solution of the governing propagation model, i.e. the nonlinear Schrödinger equation or its extensions. Specifically, we show how the network accurately predicts the temporal and spectral intensity profiles of the pulses that form upon nonlinear propagation in fibres with both anomalous and normal dispersion [2]. This data-driven approach reduces the computational time by two orders of magnitude compared to the standard process-driven method. Further, we demonstrate the ability of the NN to determine the nonlinear propagation properties from the pulses observed at the fibre output, and to classify the output pulses according to the initial pulse shape. We also expand our analysis to the case of pulse propagation in the presence of distributed gain or loss, with a special focus on the generation of self-similar parabolic pulses [3]. The network can accommodate to and maintain high accuracy for a wide dynamic range of system parameters.

We also illustrate the use of a NN to study the temporal and spectral evolutions of periodic signals made of equally frequency-spaced components upon propagation in fibre. The phase and amplitude of the frequency comb structure resulting from multi-wave mixing are accurately predicted by the network along with the corresponding high-repetition rate temporal waveform. We also emphasise how the network can learn the physical model from an experimental dataset. All these results demonstrate that a properly trained NN can greatly help the characterisation and inverse‐engineering of fibre‐based shaping systems by providing immediate and sufficiently accurate solutions.

Further, we demonstrate the possibility of using EAs to perform search and optimisation of the breathing-soliton regime in a fibre laser [4]. Contrary to the generation regimes of stationary pulses of ultrafast lasers that have been mainly addressed by previous works using EAs [5], breathing solitons exhibit a fast evolutionary behaviour, requiring dedicated real-time measurement tools for its detection [6]. Through exploration of the nonlinear cavity dynamics, which can be accessed by automated control of the nonlinear-polarisation-evolution transfer function, we show that composite merit functions, derived from specific features of the radio-frequency spectrum of the laser output, permit to achieve various self-starting breather regimes in the laser, including single breathers with controllable breathing ratio and period, and breather molecular complexes with a controllable number of elementary constituents. Our work opens novel opportunities for the exploration of highly dynamic, non-stationary operating regimes of ultrafast lasers.

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